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Population balance modelling for subcooled boiling flow of liquid nitrogen in a vertical tube

S.M. Wang, J. Wen *, Y.M. Li, S.H. Wang, Y.Z. Li

School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

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ABSTRACT

Population balance equations combined with a three-dimensional two-fluid model were employed to predict subcooled boiling flow of liquid nitrogen in a vertical upward tube. Closure correlations describing bubble nucleation and departure on the heating surface is indispensable when modeling subcooled boiling flow using a two-fluid model. Due to the small latent heat of vaporization and surface tension, nucleation and departure of nitrogen vapor bubble has different characteristics to those of high-boiling liquids. Based on the mechanism of boiling heat transfer and the unique physical properties, some important bubble model parameters were modified to be applicable to the modeling of liquid nitrogen. In this study, some modified closure correlations of the bubble departure diameter, bubble departure frequency and density of the active nucleation sites were incorporated into the frame of the two-fluid model and the CFX code. The distribution patterns of different discrete bubble classes and void fraction in the wall-heated tube were systematically analyzed. The partition of the three components of wall heat flux along the tube and the instability of bubbly flow were also studied in the paper. Good agreement was achieved on the local heat transfer coefficient against experimental measurements, which demonstrated the accuracy of the improved model.

1. Introduction

Subcooled boiling is a very common phenomenon for cryogenic fluids during transportation in pipelines. Phase change of cryogenic fluid usually occurs before the onset of thermodynamic saturation boiling due to the subcooled boiling behavior. Owning to the interphase mass transfer, fluid flow inside becomes unsteady two-phase flows which in turn significantly affect the overall design of the system. In case of the evaporation rate of liquid is too violent, the excessive gas bubbles may causes rigorous fluid flow fluctuation and triggers undesired vibration within the system, which reduces the equipment manipulation and intensifies the unsteadiness of the system. On the other hand, subcooled boiling may also promote better fluid mixing and enhance the overall heat transfer efficiency. An in-depth knowledge of the subcooled boiling phenomenon and its associated void fraction distribution is essential for design optimization. Thus, investigation of the subcooled boiling flow characteristics of cryogenic fluids (i.e. liquid nitrogen) is very interesting and important, not only from the viewpoint of the fundamental research of the hydrodynamics and thermodynamics of cryogenic fluids, but also in attempting to provide solutions to the practical engineering problems.

During the past decades, only a few experimental studies on boiling flow of nitrogen in channels have been performed due to the extremely high costs on experimental facilities and its complexity of measurement. Klimenko and Sudarchikov [1] firstly measured nitrogen boiling flows in a vertical tube and studied the effects of pressure, heat flux and mass flow rate on its overall heat transfer coefficient. The subcooled boiling in cryogenic fluids involves not only mass transfer effects due to evaporation, but also heat transfer corresponding to the latent heat of the vaporization of liquid phase. The experimental studies to date on the two-phase flow of cryogenic fluid have yielded only limited information on the basic two-phase hydrodynamic characteristics of liquid nitrogen [2,3].

On the other hand, benefit from the recent advancement of computational technique, numerical analysis can be considered as alternative tool to provide useful physical information with very limited cost requirement. Based on an unsteady thermal non-equilibrium two-fluid model, Ishimoto et al. [4] investigated the thermodynamic effect on bubble flow characteristics of liquid nitrogen in a horizontal rectangular nozzle. In his numerical model, the cryogenic two-phase flow state was approximated to a homogeneous bubbly flow with a constant bubble diameter and cannot supply sufficient information. Li et al. [5] numerically simulated

* Corresponding author. Address: Department of Refrigeration and Cryogenics Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China. Mobile: +86 13201606129; fax: +86 29 82668725.
E-mail address: jianwen@mail.xjtu.edu.cn (J. Wen).

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Nomenclature

a_{if}	interfacial area concentration, m^{-1}
A_q	fraction of wall area subjected to quenching
c_f	increase coefficient of surface area
C_p	specific heat, J/kg K
d	parent particle diameter, m
d_{BW}	bubble departure diameter, m
d_i; d_j	daughter particle diameters, m
d_{ij}	equivalent diameter, m
D_B	death rate due to break-up, $m^{-3}\ s^{-1}$
D_C	death rate due to coalescence, $m^{-3}\ s^{-1}$
f	bubble departure frequency, s^{-1}
F_{lg}	the total interfacial force
f_{BV}	breakage volume fraction
f_i	scalar fraction of each bubble size group
F_{lg}	total interfacial force, N
F_{lg}^{drag}	drag force, N
F_{lg}^{lift}	lift force, N
$F_{lg}^{lubrication}$	wall lubrication force, N
$F_{lg}^{dispersion}$	turbulent dispersion force, N
g	gravitational acceleration, $m\ s^{-2}$
$\vec{g}$	gravitational vector, $m\ s^{-2}$
h	inter-phase heat transfer coefficient
h_0	initial film thickness, m
h_f	critical film thickness at rupture, m
h_{fg}	latent heat, J/kg
H	enthalpy, J/kg
k	thermal conductivity, W/m K
n	density of active nucleation sites
n_i	number density of the ith class, m^{-3}
n_j	number density of the jth class, m^{-3}
N	number of bubble classes
P	pressure, Pa
P_B	production rate due to break-up, $m^{-3}\ s^{-1}$
P_C	production rate due to coalescence, $m^{-3}\ s^{-1}$
Q_w	wall heat flux, W/m^2
Q_c	heat transferred by convection, W/m^2
Q_e	heat transferred by evaporation, W/m^2
Q_q	heat transferred by quenching, W/m^2
S_i	source term due to coalescence and break-up, kg/m^3 s
St	stanton number
t	time, s
T	temperature, K
t_{ij}	coalescence time, s
T_{sat}	saturation temperature, K
T_{sub}	subcooling temperature, K
u	velocity, $m\ s^{-1}$
$\vec{u}$	velocity vector, $m\ s^{-1}$
u_t	velocity due to turbulent collision, $m\ s^{-1}$

Greek symbols

α	void fraction
$\Delta\rho$	density difference = $\rho_l - \rho_g$, kg/m^3
ε	dissipation of kinetic energy, $m^2\ s^{-2}$
θ	bubble contact angle, rad
λ^e	effective thermal conductivity, W/m K
μ^e	effective viscosity, kg/m s
μ_t	turbulent velocity $m\ s^{-1}$
ρ	density, kg/m^3
σ	surface tension, kg/s^2
ξ	ize ratio between an eddy and a particle in the inertial sub-range
τ_{BW}	bubble departure time
τ_w	bubble waiting time
τ_{ij}	bubble contact time, s
Γ	mass transfer rate, kg/m^3 s
χ	coalescence rate, $m^{-3}\ s^{-1}$
Ω	break-up rate, $m^{-3}\ s^{-1}$

Subscripts

g	gas
gl	transfer of quantities from liquid phase to gas phase
l	liquid
lg	transfer of quantities from gas phase to liquid phase
min	minimum
w	wall

the boiling flow of liquid nitrogen in a vertical tube using the two-fluid model. They all directly used the empirical correlations from water properties in their simulation of liquid nitrogen. In general, cryogenic fluids are characterized by large compressibility, small latent heat of vaporization, compared with fluids that are liquid at room temperature such as water. These unique characteristics of cryogenic fluids indicate that the existing empirical models which is calibrated and verified for water are invalid for cryogenic fluids. It is important to derive a new relationship for the cryogenic fluids with distinct thermal properties. The study of Tu [6] and Yeoh [7] demonstrated that the closure relationships or parameters are important for an accurate prediction of subcooled boiling: (1) partition of the wall heat flux; (2) bubble size distribution and interfacial area concentration; and (3) bubble departure diameter and its relationship with bubble frequency. Among multidimensional theoretical description of boiling flow, the most widely used approach appears to be two-fluid modeling. Lately, increasing interest in population balances have resulted in a number of significant developments especially towards modeling bubbly flows [8–12]. Up to now, a thorough research study on the cryogenic fluid bubbly flows using the Population Balance Model is still outstanding.

The two-fluid model is basically included in the commercial CFD code CFX-4.4 and previously used for predicting subcooled boiling flow of water at room temperature. In this paper, a study has been conducted by incorporating the Population Balance Equations and new closure models to extend the two-fluid model into being applicable to liquid nitrogen. The subcooled boiling flow of liquid nitrogen in an upward vertical tube was numerically simulated using the improved two-fluid model with modified coefficients for cryogenic fluids.

2. Subcooled boiling models

In a two-phase mechanistic model, both the gas and liquid phases are treated as continua, and two sets of conservation equations governing the balance of mass, momentum and energy of each phase are solved. Consider the interfacial mass, momentum and energy transfer, the governing equations for the two-fluid model are given by:

2.1. Two-fluid model

Continuity equation of liquid phase:

$$\frac{\partial(\rho_l\alpha_l)}{\partial t} + \nabla\cdot(\rho_l\alpha_l\vec{u}_l) = \Gamma_{lg} \tag{1}$$

Continuity equation of gas phase: